

# Components of the elliptic flow in Pb-Pb collisions at $\sqrt{s} = 2.76\text{TeV}$

Piotr Bożek<sup>a,b</sup>,

<sup>a</sup>*Institute of Physics, Rzeszów University, ul. Rejtana 16, 35-959 Rzeszów, Poland*

<sup>b</sup>*The H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland*

---

## Abstract

We calculate the elliptic flow of charged particles in Pb-Pb collisions at  $\sqrt{s} = 2.76\text{TeV}$  in relativistic viscous hydrodynamics. The recent data of the ALICE Collaboration on the elliptic flow as function of the centrality can be very well described using the hydrodynamic expansion of a fluid with a small shear viscosity  $\eta/s = 0.08$ . The elliptic flow as function of the transverse momentum shows systematic deviations from a hydrodynamic behavior in the small momenta region  $p_\perp < 800\text{MeV}$ . It indicates that a non-negligible contribution of non-thermalized particles from jet fragmentation is present.

---

PACS: 25.75.-q, 25.75.Dw, 21.65.Qr

The elliptic flow measurements in heavy-ion collisions at the Large Hadron Collider (LHC) have been presented [1]. Generally, the results are similar as observed at lower energies at the Relativistic Heavy Ion Collider (RHIC). The elliptic flow coefficient  $v_2(p_\perp)$  as function of the transverse momentum is increasing with  $p_\perp$  and saturates at higher momenta. The elliptic flow as function of the centrality of the collision reflects the initial eccentricity of the fireball at each centrality. The elliptic flow is generated in a collective expansion of the dense matter created in the collision, the comparison to model calculations can provide valuable information on the dynamics of the collisions, on the equation of state and the transport coefficients of the dense, hot matter [2,3].

The integrated elliptic flow as function of the collision centrality can be used to extract the properties of the fluid in the expanding fireball. Analyzes of the elliptic flow in heavy-ion collisions at RHIC energies indicate that the dense matter is an almost perfect fluid [4,5]. The ALICE data from Pb-Pb collisions at  $\sqrt{s} = 2.76\text{TeV}$  give smaller  $v_2$  than expected from perfect fluid hydrodynamics with hadronic rescattering [6]. The comparison of viscous hydrodynamic results with data at RHIC and LHC show no noticeable change

in the shear viscosity coefficient with the energy [7]. Analysis of the LHC data at different centralities in terms of the Knudsen number points towards a small value of the shear viscosity [8]. The observed elliptic flow can be partly reproduced in a hadron rescattering model with a short formation time [9].

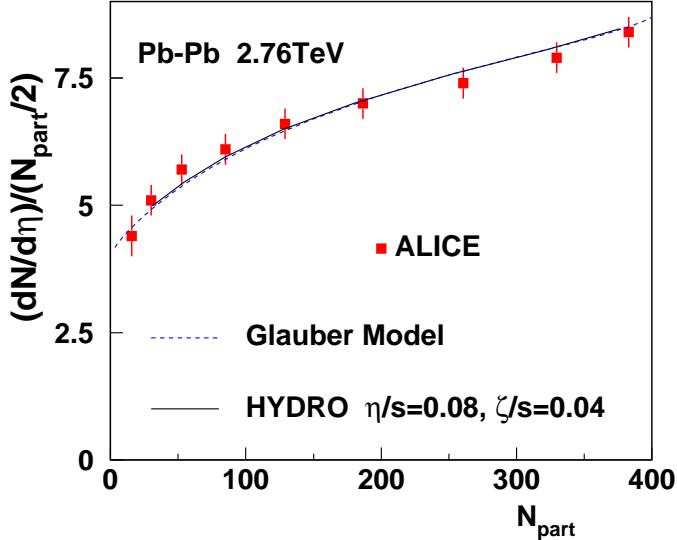


Fig. 1. Charged particle multiplicity density in pseudorapidity per participant pair for Pb-Pb collisions at  $\sqrt{s} = 2.76$  TeV from the Glauber model (dashed line), and from viscous hydrodynamic calculations (solid line) together with the ALICE data [10].

In the following we present an analysis of the ALICE results for the charged particle elliptic flow in the second order viscous hydrodynamic model with shear and bulk viscosities [11]. Particle production in the central region at the LHC is described in the 2+1-dimensional, boost-invariant hydrodynamics. The shear viscosity to entropy ratio is  $\eta/s = 1/4\pi$  and the bulk viscosity is non-zero in the hadronic phase with  $\zeta/s = 0.04$ . The initial entropy density of the fireball in the transverse plane is taken from the Glauber model, at the impact parameter  $b$

$$s(x, y) = s_0 \frac{(1 - \alpha)\rho_{part}(x, y, b) + 2\alpha\rho_{bin}(x, y, b)}{(1 - \alpha)\rho_{part}(0, 0, 0) + 2\alpha\rho_{bin}(0, 0, 0)}, \quad (1)$$

with  $\rho_{part}$  and  $\rho_{bin}$  the participant nucleons and binary collisions densities. The details of the hydrodynamic model calculation and the parameters for Pb-Pb collisions at the LHC can be found in [12,11]. The statistical emission at the freeze-out and resonance decays are done using the THERMINATOR event generator [13]. The parameter  $\alpha = 0.15$  reproduces the centrality dependence of the density of charged particles in pseudorapidity  $\frac{dN}{d\eta}$  measured by the

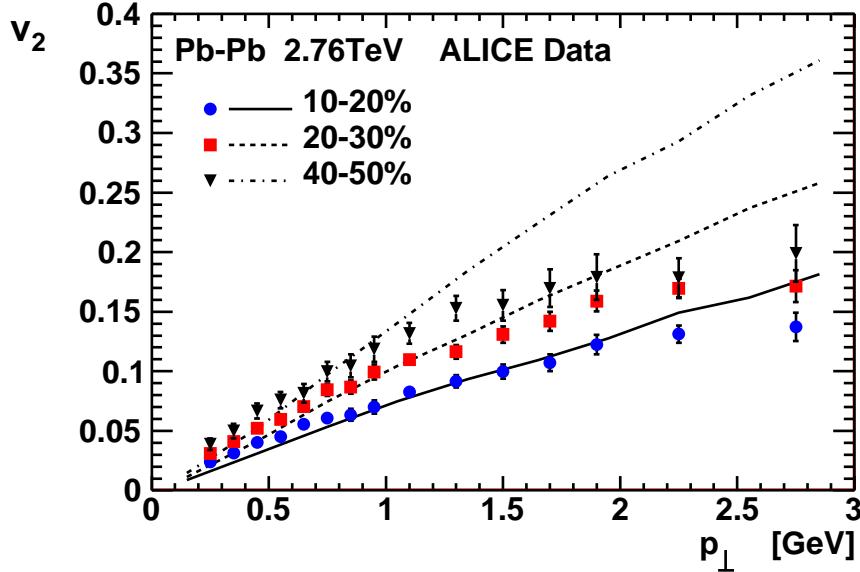


Fig. 2. Elliptic flow coefficient of charged particles as function of transverse momentum measured by the ALICE Collaboration [1] (symbols) together with the results of viscous hydrodynamics (lines) for three centrality classes.

ALICE Collaboration

$$\frac{dN}{d\eta} = \frac{dN_{pp}}{d\eta} \left( \frac{1 - \alpha}{2} N_{part} + \alpha N_{bin} \right) \quad (2)$$

(dashed line in Fig 1), where  $dN_{pp}/d\eta$  is the multiplicity density in inelastic proton-proton collisions,  $N_{part}$  and  $N_{bin}$  are the average numbers of participants and of binary collisions for a given centrality. The entropy density at the center of the fireball  $s_0$  in Eq. 1 is adjusted to reproduce the multiplicity in the most central Pb-Pb collisions, taking into account the entropy production in the viscous hydrodynamic evolution. The results of the hydrodynamic calculation (solid line in Fig. 1) follow closely the Glauber model input and reproduce the data on the centrality dependence of the multiplicity [10].

For each centrality class the elliptic flow of charged particles as function of the transverse momentum is calculated in the reaction plane (Fig. 2). For central collisions (10-20%) the results of the hydrodynamic calculation follow the data up to  $p_{\perp} \simeq 2. For more peripheral collisions (40-50%) the data show a saturation of the increase of  $v_2$  with  $p_{\perp}$  around 1.2GeV, while the calculated  $v_2(p_{\perp})$  keeps growing with the transverse momentum. The change in the behavior of the elliptic flow coefficient with  $p_{\perp}$  is expected. The production of particles with small momenta  $p_{\perp} < 1-2$ GeV is dominated by the statistical emission from a thermalized fluid. The asymmetry of the flow of the fluid comes from the hydrodynamic evolution of a source with an initial azimuthal eccentricity. On the other hand, particles at high momenta originate from jet fragmentation [14,15]. Differences in the path length in different directions in$

the fireball, lead via jet quenching to an azimuthal asymmetry of the final particles. While it is expected that the hydrodynamic results deviate from the data at high transverse momenta, we observe also a systematic deviation of the data points from the calculation in the range  $200\text{MeV} < p_\perp < 800\text{MeV}$ . We discuss about this effect latter.

In Fig. 3 is shown the integrated elliptic flow  $v_2$  for different centralities of the collision ( $|\eta| < 0.8$ ,  $200\text{MeV} < p_\perp < 5\text{TeV}$ ). The hydrodynamic model using Glauber model initial sources, with shear viscosity  $\eta/s = 0.08$  and bulk viscosity  $\zeta/s = 0.04$  reproduces the experimental observations very well. It means that, for the chosen initial eccentricity, the expansion of the fluid with a minimal shear viscosity describes the data. The analogous calculation for Au-Au collisions at  $200\text{GeV}$  describes well the RHIC data for the integrated  $v_2$  using the same value  $\eta/s = 0.08$ . The precise value of the shear viscosity coefficient compatible with the data depends on the model of the initial eccentricity, with color glass condensate initial conditions leading to larger values of  $\eta/s$  [4,5]. We note that the Glauber binary collisions profiles of the initial energy density used in Ref. [7] result in up to 20% larger initial eccentricities in central collisions than Eq. 1, which would imply a larger value of  $\eta/s$  to reproduce the data.

Despite the apparent success of the hydrodynamic description of the average elliptic flow in Pb-Pb collisions at the LHC as presented in Fig. 3, the result must be taken with caution. The differential elliptic flow coefficient  $v_2(p_\perp)$  is not described by the hydrodynamic model, neither at high momenta, which is natural, nor at small momenta  $p_\perp < 800\text{MeV}$ . If the elliptic flow originates from the collective flow of the fluid, the behavior at small momenta is linear in the transverse momentum (for particles with a small mass)

$$v_2(p_\perp) \propto p_\perp. \quad (3)$$

Such a dependence is observed in hydrodynamic calculations (also including viscosity corrections) and in experiments on heavy-ion collisions at RHIC.

The elliptic flow measured at the LHC is not increasing linearly with the momentum. The observed differential elliptic flow  $v_2(p_\perp)$  is larger than in hydrodynamic calculations. The extrapolation of the measured elliptic flow to zero momentum is not going through the point  $v_2(0) = 0$ , as it should for the elliptic flow of a collective origin (Fig. 4). A linear fit to the data points with  $p_\perp < 1\text{GeV}$  gives an intercept of  $0.06-0.01 \pm 10^{-5}$ , a small but statistically significant and systematic deviation from zero. Moreover, the extrapolation of the results of hydrodynamic calculations would lead to a negative intercept. It is due to the fact that for massive particles we have  $v_2(p_\perp) \propto p_\perp^2$ . While it is expected that hydrodynamic results deviate from the data at high momenta, it is very difficult to explain the excess of the observed elliptic

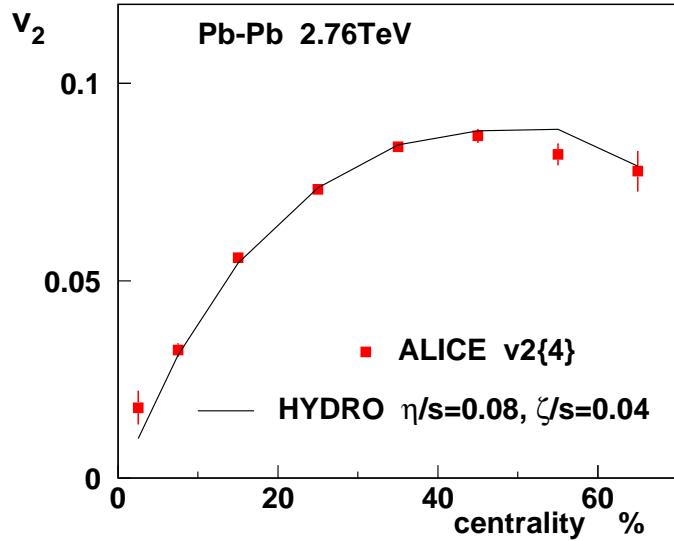


Fig. 3. Elliptic flow coefficient in Pb-Pb collisions as function of centrality, ALICE Collaboration data [1] compared to viscous hydrodynamic results.

flow at small momenta  $p_{\perp} < 800\text{MeV}$ . The data points lie above the linear function from hydrodynamic calculations for all centralities in the range  $200\text{MeV} < p_{\perp} < 800\text{MeV}$ . The additional shift of the measurements above the calculated values is about 0.01-0.02. One possibility is that the linear behavior happens at very small momenta  $p < 200\text{MeV}$ , not observed experimentally. The data points observed by the ALICE Collaboration ( $p_{\perp} > 200\text{MeV}$ ) would correspond to the region of strong viscous correction, with deviations from the linear behavior. In the upper panel of Fig. 4 is shown an example of a calculation starting with initial eccentricity increased by a factor 1.5 and with  $\eta/s = 0.24$ . Such a calculation gives the same integrated elliptic flow as observed experimentally. The calculated elliptical flow coefficient  $v_2(p_{\perp})$  is closer to the data points, but still a systematic deviation is visible for small momenta.

The elliptic flow in hydrodynamic models originates predominantly from the azimuthal asymmetry of the collective flow velocity. On general grounds, one expects a linear behavior of  $v_2(p_{\perp})$  for light particles at small momenta. There is a different mechanism generating the azimuthal asymmetry, related to the asymmetry of surface of the emission. Due to strong jet quenching in the dense matter, the escaping partons originate from the surface of the fireball. In peripheral collisions the geometrical asymmetry of the source leads to preferential emission of escaping partons in-plane. The elliptic flow coefficient of the emitted partons would be approximately independent of the parton momentum [16]. The final observed hadrons are distributed in a cone around the direction of the fragmenting jet parton.

At the LHC energies, in each Pb-Pb collision many jets are formed. The jets

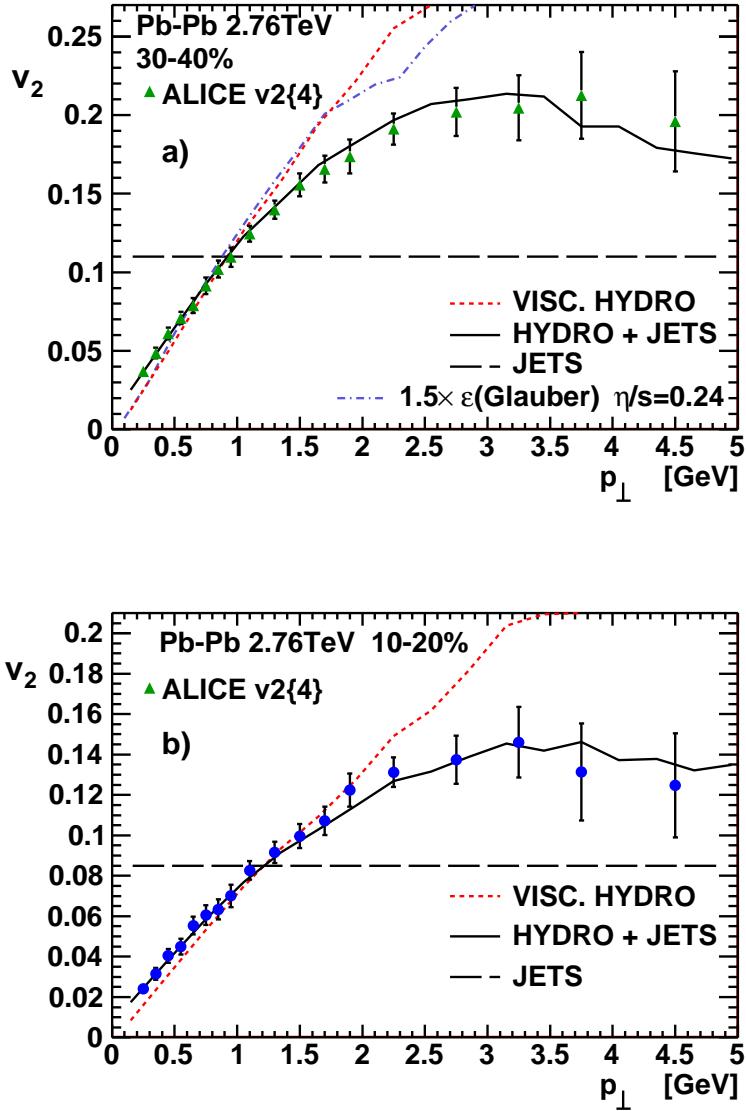


Fig. 4. Elliptic flow coefficient of charged particles as function of transverse momentum for centrality 30-40% (upper panel) and 10-20% (lower panel) measured by the ALICE Collaboration [1]. The dotted line represents viscous hydrodynamic results, the dashed line the approximate elliptic flow from jet fragmentation and the solid line the weighted mixture of the jet and hydrodynamic contributions (Eq. 4). The dashed-dotted line in the upper panel represents the elliptic flow obtained increasing the Glauber model initial eccentricity by 50% and using  $\eta/s = 0.24$ .

interact with the dense matter in the fireball, leading to jet quenching and jet asymmetry [17,18]. The interaction of the jet parton with the matter in the fireball, depends on the path it travels, which leads to an azimuthal asymmetry of the particle emission at large transverse momenta. The elliptic flow coefficient at large momenta at the RHIC energies is approximately indepen-

dent of the momentum and is of the order of 0.05-0.12, depending on the centrality [19,20]. The value of the elliptic flow coefficients from jets at momenta  $p_\perp < 1\text{GeV}$  is not known experimentally, as this region is dominated by the statistical emission from the thermalized fluid. Once the direction of the jet parton is fixed, the fragmenting hadrons inherit, to a large extent, the original direction of the jet. A particle of momentum  $\simeq 200\text{-}800\text{MeV}$  is not the leading particle in the fragmentation of the jet, it originates as one of the soft particles in the fragmentation of a parton with the momentum of a few GeVs. The leading particle is emitted in a narrow cone around the jet parton. The correlation between a high momentum trigger particle (leading particle) and associated particles show that also the soft particles are emitted in a cone around the jet direction. Although, one expects the jet cone opening is larger for particles with small momenta, we assume that the elliptic flow coefficient from jets is approximately constant down to 200MeV for this first estimate.

Following the parameterization of Ref. [21], we write the elliptic flow coefficient at a given momentum as the sum of two components, a jet component  $v_2^{jet}$  and a hydrodynamic component  $v_2^{hydro}$

$$v_2(p_\perp) = (1 - g(p_\perp))v_2^{hydro}(p_\perp) + g(p_\perp)v_2^{jet}(p_\perp) , \quad (4)$$

$g(p_\perp)$  denotes the proportion of particles originating from jet fragmentation at a given momentum. It implicitly assumes that the jet particles, accounted for in the weight  $g(p_\perp)$ , are particles that do not thermalize and conserve their original (non-hydrodynamic)  $v_2$ . There are only few constraints on the form of  $v_2^{jet}$  and  $g(p_\perp)$ ;  $g \simeq 1$  at large momenta and, from the deviation of the ALICE data away from the linear function  $v_2(p_\perp) \propto p_\perp$ , we have  $g(p_\perp)v_2^{jet}(p_\perp) \simeq 0.01\text{-}0.02$  for  $p_\perp < 800\text{MeV}$ . For illustration, we fix the parameters [21] as  $g(p_\perp) = (1 + \tanh((p - p_w)/\Delta p))/2$ ,  $p_w = 2.8\text{GeV}$ ,  $\Delta p = 2.8\text{GeV}$ ,  $v_{jet}(p_\perp) = 0.11$  for centrality 30-40% and  $p_w = 3.2\text{GeV}$ ,  $\Delta p = 3.0\text{GeV}$ ,  $v_{jet}(p_\perp) = 0.085$  for centrality 10-20%. The final elliptic flow coefficient from the two components is denoted by the solid lines in Fig. 4. The deviation of the data from the hydrodynamic calculation in the range  $200\text{MeV} < p_\perp < 800\text{MeV}$  can be explained as due to a 10-20% contribution of jet particles. For soft particles emerging from a jet parton, one expects some reduction of  $v_2^{jet}(p_\perp)$  for small momenta, due to a larger jet cone opening or to a possible coalescence with thermal partons. This would imply a larger value of  $g(p_\perp)$  to get a similar  $v_2^{jet}(p_\perp)g(p_\perp)$ .

We present results of relativistic viscous hydrodynamic calculations for Pb-Pb collisions at  $\sqrt{s} = 2.76\text{TeV}$ . The initial density for the evolution is fixed using the experimental results for the charged particle multiplicity as function of the centrality. The same calculation was shown to describe correctly the observed interferometry radii in central collisions at the LHC [12]. The hydrodynamic calculation using Glauber model initial profiles and a small shear viscosity coefficient reproduces the integrated elliptic flow coefficient observed

by the ALICE Collaboration. Surprisingly, the differential elliptic flow as function of the transverse momentum  $v_2(p_\perp)$  shows systematic deviations from the hydrodynamics estimate. At small momenta the data points lie above the linear hydrodynamic behavior  $v_2(p_\perp) \propto p_\perp$ . It is a very unexpected result. In the small transverse momentum region, besides the dominant statistical emission from a collectively expanding fluid, a non-negligible contribution from jets appears. This observation, if confirmed by further experimental studies, indicates that at the LHC energies non-thermalized particles from jet fragmentation constitute a substantial part of the soft spectrum. This additional source of particles with soft momenta should be taken into account in quantitative studies of hydrodynamic models of heavy-ion collisions, in calculating the spectra and the elliptic flow of particles. On the other hand, it could serve as a new frontier of studies of the jet parton formation, attenuation and fragmentation in a heavy-ion environment. In particular, the fact that particles with soft momenta do not thermalize shows that the jet fragmentation occurs *outside* of the thermal fireball.

**Acknowledgments:** The author thanks Raimond Snellings for providing the experimental data. Research supported in part by the MNiSW grant No. N N202 263438.

## References

- [1] K. Aamodt, *et al.*, ALICE, arXiv: 1011.3914.
- [2] J. Y. Ollitrault, Phys. Rev., **D46** (1992) 229.
- [3] S. A. Voloshin, A. M. Poskanzer, R. Snellings, arXiv: 0809.2949.
- [4] M. Luzum, P. Romatschke, Phys. Rev., **C78** (2008) 034915.
- [5] H. Song, U. W. Heinz, J. Phys., **G36** (2009) 064033.
- [6] T. Hirano, P. Huovinen, Y. Nara, Phys. Rev. C, **83** (2011) 021902.
- [7] M. Luzum, arXiv: 1011.5173.
- [8] R. A. Lacey, A. Taranenko, N. N. Ajitanand, J. M. Alexander, Phys. Rev. C, **83** (2011) 031901.
- [9] T. J. Humanic, arXiv: 1011.5853.
- [10] K. Aamodt, *et al.*, ALICE, Phys. Rev. Lett., **106** (2011) 032301.
- [11] P. Bożek, Phys. Rev., **C81** (2010) 034909.
- [12] P. Bożek, arXiv: 1012.5927.

- [13] A. Kisiel, T. Taluć, W. Broniowski, W. Florkowski, *Comput. Phys. Commun.*, **174** (2006) 669.
- [14] U. A. Wiedemann, arXiv: 0908.2306.
- [15] D. d'Enterria, B. Betz, *Lect. Notes Phys.*, **785** (2010) 285.
- [16] E. V. Shuryak, *Phys. Rev.*, **C66** (2002) 027902.
- [17] G. Aad, *et al.*, ATLAS, arXiv: 1011.6182.
- [18] K. Aamodt, *et al.*, ALICE, *Phys. Lett.*, **B696** (2011) 30.
- [19] S. Afanasiev, *et al.*, PHENIX, *Phys. Rev.*, **C80** (2009) 054907.
- [20] A. Adare, *et al.*, PHENIX, *Phys. Rev. Lett.*, **105** (2010) 142301.
- [21] J. Liao, V. Koch, *Phys. Rev. Lett.*, **103** (2009) 042302.